

**CENTER FOR COASTAL PHYSICAL OCEANOGRAPHY
COLLEGE OF SCIENCES
OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA 23529**

**STUDYING THE EARTH'S ENVIRONMENT FROM SPACE:
COMPUTER LABORATORY EXERCISED AND INSTRUCTOR
RESOURCES**

By
Dr. Elizabeth A. Smith
Center for Coastal Physical Oceanography
Old Dominion University

And

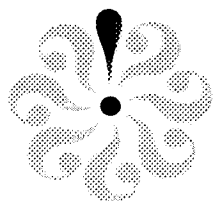
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Department of Science
United States Coast Guard Academy

Interim Report
June 1997-June 1998

Prepared for
NASA Goddard Space Flight Center
Attn.: Dr. Nahid Khazenie, Technical Officer
Code 170.0
Greenbelt, MD 20771

Under
Grant No. NAG5-4515

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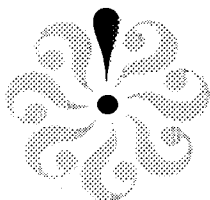
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**Studying the Earth's Environment From Space:
Computer Laboratory Exercises
and Instructor Resources
(NAG-5-4515)**

First Year Report (June 1997-June 1998)

Principle Investigators:

Elizabeth A. Smith
Center for Coastal Physical Oceanography
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and

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Department of Science
United States Coast Guard Academy

INTRODUCTION

Studying the Earth's Environment From Space is a two-year project to develop a suite of CD-ROMs containing Earth System Science curriculum modules for introductory undergraduate science classes. Lecture notes, slides, and computer laboratory exercises, including actual satellite data and software, are being developed in close collaboration with Carla Evans of NASA GSFC Earth Sciences Directorate Scientific and Educational Endeavors (SEE) project. Smith and Alfultis are responsible for the Oceanography and Sea Ice Processes Modules. The GSFC SEE project is responsible for Ozone and Land Vegetation Modules. This document constitutes a report on the first year of activities of Smith and Alfultis' project.

ACCOMPLISHMENTS

- Initiated collaboration w/ GSFC SEE project to eliminate duplication of effort and exploit disciplinary strengths. Smith and/or Alfultis have met with members of the GSFC SEE Team four times in the past year.
- Acquired and processed global and regional SST data from NOAA and NASA/JPL PO.DAAC archives. See Figures 1 and 2 for examples. As proposed, data processing includes annotating the images for ease of use and interpretation by students.
- Version 1 of Ocean Circulation/SST exercises were used by CDR Alfultis at the Coast Guard Academy(CGA) in Spring 1998.
- GSFC SEE Ozone exercises were also used by CDR Alfultis at CGA in Spring 1998.
- Lessons learned at CGA, for both SST and Ozone, have been incorporated into new versions of software and exercises.

PRESENT STATUS

Following will be completed by 8/15/98:

- Scientific discussion for Ocean Circulation/SST. (attached)
- Version 2 of Ocean Circulation/SST exercises. (attached)
- Scientific discussion for Sea Ice Processes.
- Version 1 of Sea Ice Processes exercises. (attached)
- Acquire and process monthly sea ice concentration data from NSIDC DAAC.
- Present paper at IGARSS '98 in Seattle. (7/6/98)
- Draft of CZCS/SeaWiFS Phytoplankton Pigment Concentration science discussion and exercises. (Outline attached)
- Initiate discussion with JPL PO.DAAC for production and distribution of beta test CD-ROMs and assessment tools to selected undergraduate instructors.

PLANS for SECOND YEAR

- Complete Ocean Circulation/SST, Phytoplankton Pigment Concentration, and Sea Ice Processes Modules.
- Work with NASA Classroom of the Future and West Chester University regarding development of assessment tools.
- Develop El Nino and Indian Ocean Monsoon case studies using multiple data sets.
- Develop tutorials and instructor answer keys for all modules.
- First training workshop at ODU in Summer 1999.

PROJECT CONTENT OUTLINE

We envision the content and structure of the Ocean Circulation/SST and Sea Ice Modules to be as follows:

I. Ocean and Atmospheric Interactions Module

A. Ocean Circulation and Sea Surface Temperature (SST)

Science Discussion

1) Global SST Distribution

- * surface heat budget
- * global mean SST distribution
- * ocean currents
- * ocean winds (Ekman spiral, upwelling)
- * daily SST variations
- * seasonal SST variations (including Indian Monsoon)
- * interannual SST and sea surface height variations (El Nino)

2) Determining SST from Infrared Observations

- * radiation principles
- * sources of IR energy received at satellite
- * atmospheric absorption windows in the IR
- * AVHRR
- * atmospheric sources of error
- * removing atmospheric sources of error
- * derivation of SST

3) Computer Laboratory Exercises

- * Geographical distribution of SST
- * Seasonal cycle and ocean seasons
- * Interannual variability

B. Ocean Productivity and Phytoplankton Pigment Concentration

1) Scientific Discussion

2) Determining phytoplankton pigment concentration from Satellite Observations

3) Computer Laboratory Exercises

- * Geographical distribution of SST
- * Seasonal cycle and ocean seasons
- * Interannual variability

C. CASE STUDIES for Laboratory Computer Exercises Using Multiple Data Sets

1) El Nino

- * qualitative inspection of selected data
- * creation and plotting of time series
- * computation of SST anomaly fields
- * introduction of sea surface height anomaly image
- * plot profiles along the equator from east to west
- * compare SST and sea surface height
- * compare precipitation and water vapor data

2) Indian Ocean Monsoon

- * qualitative inspection of selected data
- * creation and plotting of time series
- * introduction of sea surface height anomaly image
- * plot profiles
- * compare SST and sea surface height
- * compare precipitation and water vapor data

II. Polar Sea Ice Processes Module

A. Science Discussion

1) Global distribution

- * surface heat budget
- * definition of sea ice and types
- * definition of polynya and types
- * Northern Hemisphere
 - seasonal cycle
 - max and min distribution
 - marginal ice zone
 - ocean currents
 - polynyas
- * Southern Hemisphere
 - seasonal cycle
 - max and min distribution
 - marginal ice zone
 - ocean currents
 - polynyas

2) Determining sea ice concentration from Microwave Observations

- * radiation principles
- * sources of microwave radiation received at satellite
- * atmospheric influences/windows
- * SSMI sensor
- * inferring ice concentration

B. Computer Laboratory Exercises

For each hemisphere:

- 1) Global distribution and seasonal cycle.
- 2) Estimation of seasonal growth rates.
- 3) Determination of total areal extent for minimum and maximum extent.
- 4) Interannual variation of maximum extent.

Figure 1. Example of a fully annotated global SST image for December 1996. These data are available for January 1982-present, as monthly averaged images.

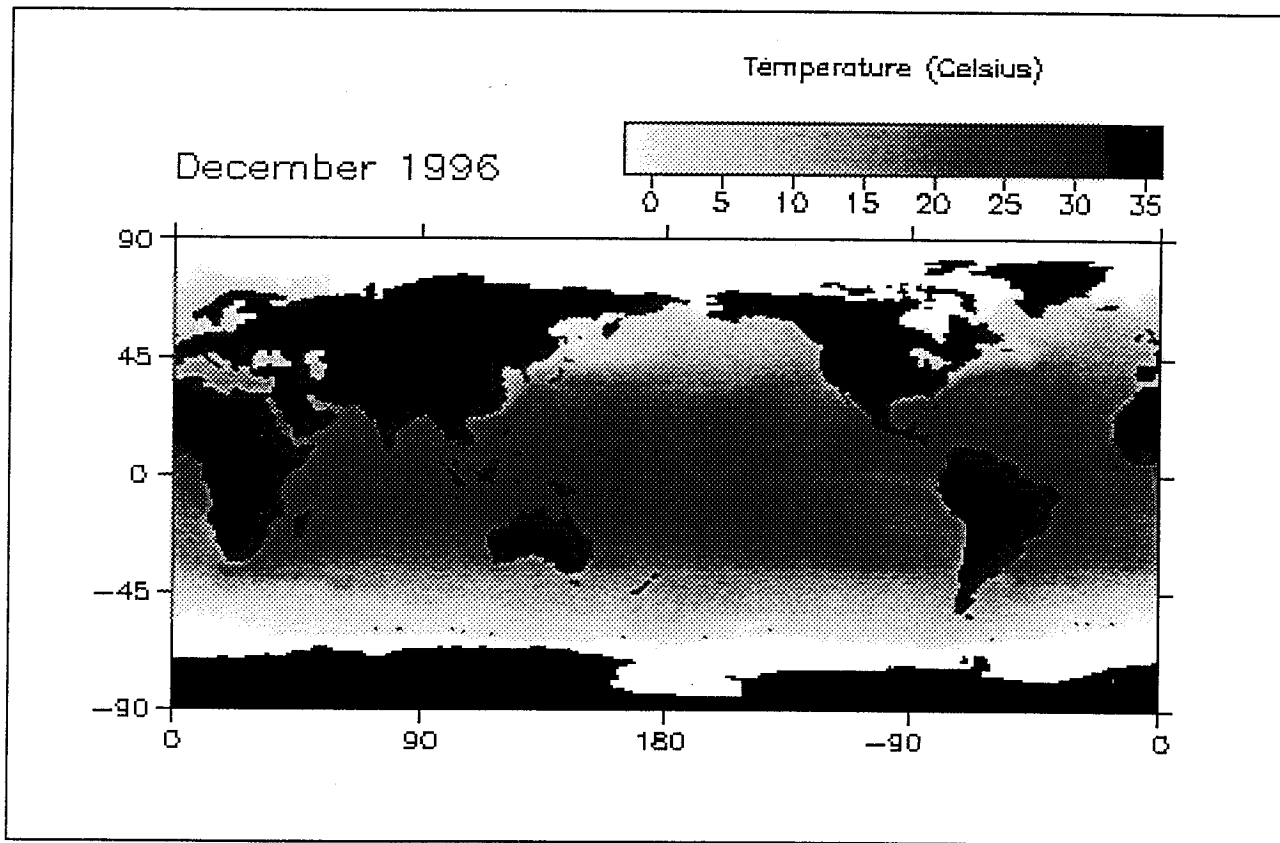
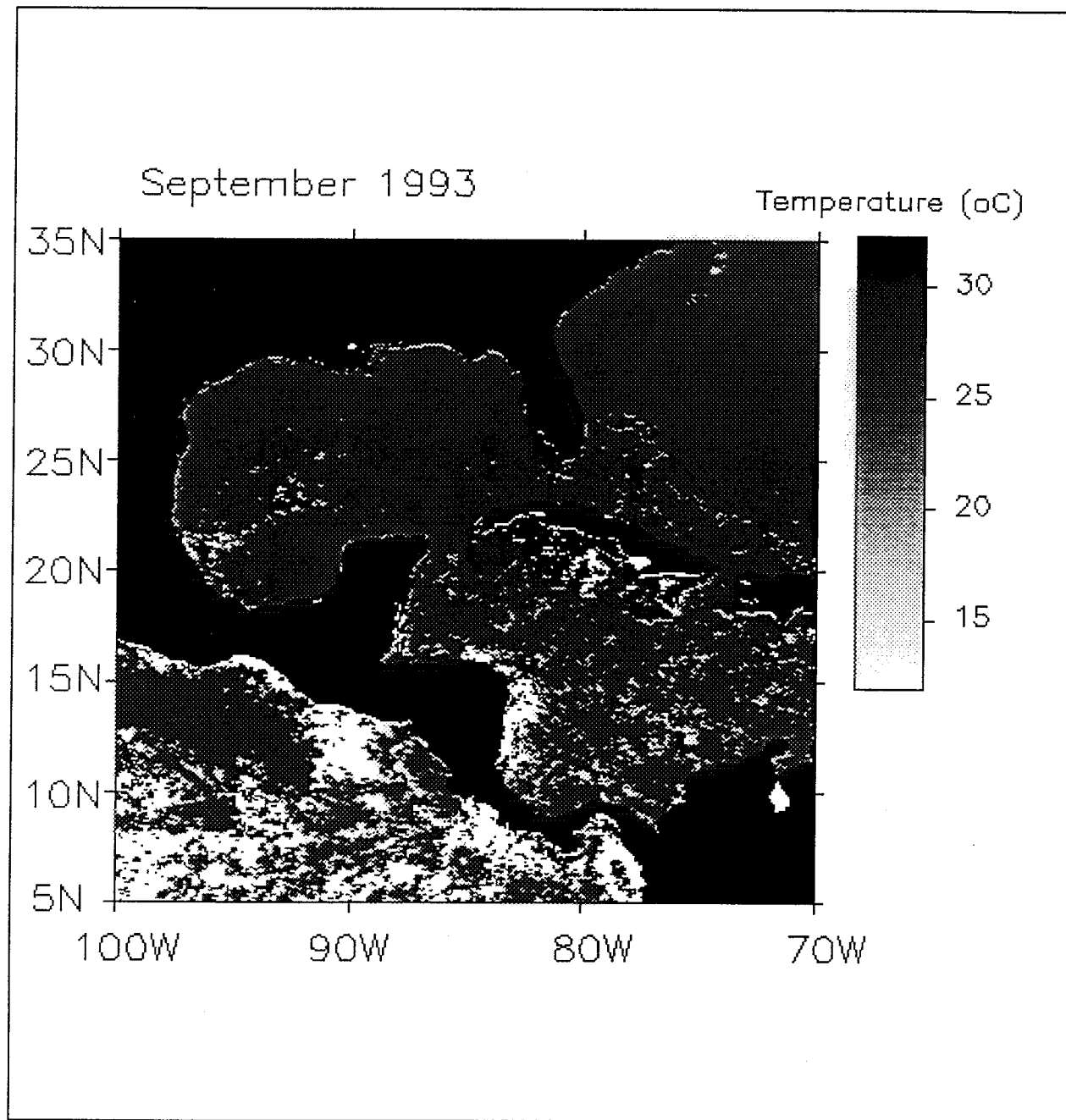


Figure 2. Example of a fully annotated, high-resolution Gulf of Mexico SST image for September 1993. These data are available for the Gulf Stream, Arabian Sea and U.S. West Coast areas.



Global Sea Surface Temperature Distribution and Satellite Sea Surface Temperature Observations -Scientific Background

Global Sea Surface Temperature Distribution

Outline

- I. Surface Heat Budget
- II. Global Mean Sea Surface Temperature Distribution
- III. Movement of Water by Ocean Currents
- IV. Movement of Water by Winds
- V. Daily Warming/Cooling of Sea Surface
- VI. Seasonal Warming/Cooling of Sea Surface
- VII. Interannual Warming/Cooling of Sea Surface

Surface Heat Budget

In this section, we will examine the processes which affect the global distribution of sea surface temperature (SST). The global SST distribution is governed by the sources and sinks of heat at the surface. The ocean surface will heat up if it receives more heat than it loses, and conversely, will get cooler if it loses more heat than it receives. The ocean surface receives heat due to (Figure 1):

1. Incoming shortwave radiation from the sun.
2. Incoming longwave radiation from the atmosphere.
3. Conduction of sensible heat from warmer air towards cooler water.
4. Gain of latent heat through condensation.
5. Movement (advection) of warmer water into a region (Not shown).

It loses heat by (Figure 1):

6. Emitted longwave radiation from the surface to the atmosphere.
7. Conduction of sensible heat from warmer water towards cooler air.
8. Loss of latent heat through evaporation.
9. Movement (advection) of cooler water into a region (Not shown).

Figures () and () illustrate the amount of incoming radiation from the sun at the top of the atmosphere during the summer and winter solstices. Based on these figures, what do you expect the global distribution of SST to look like? How do you think the SST distribution will vary with season?

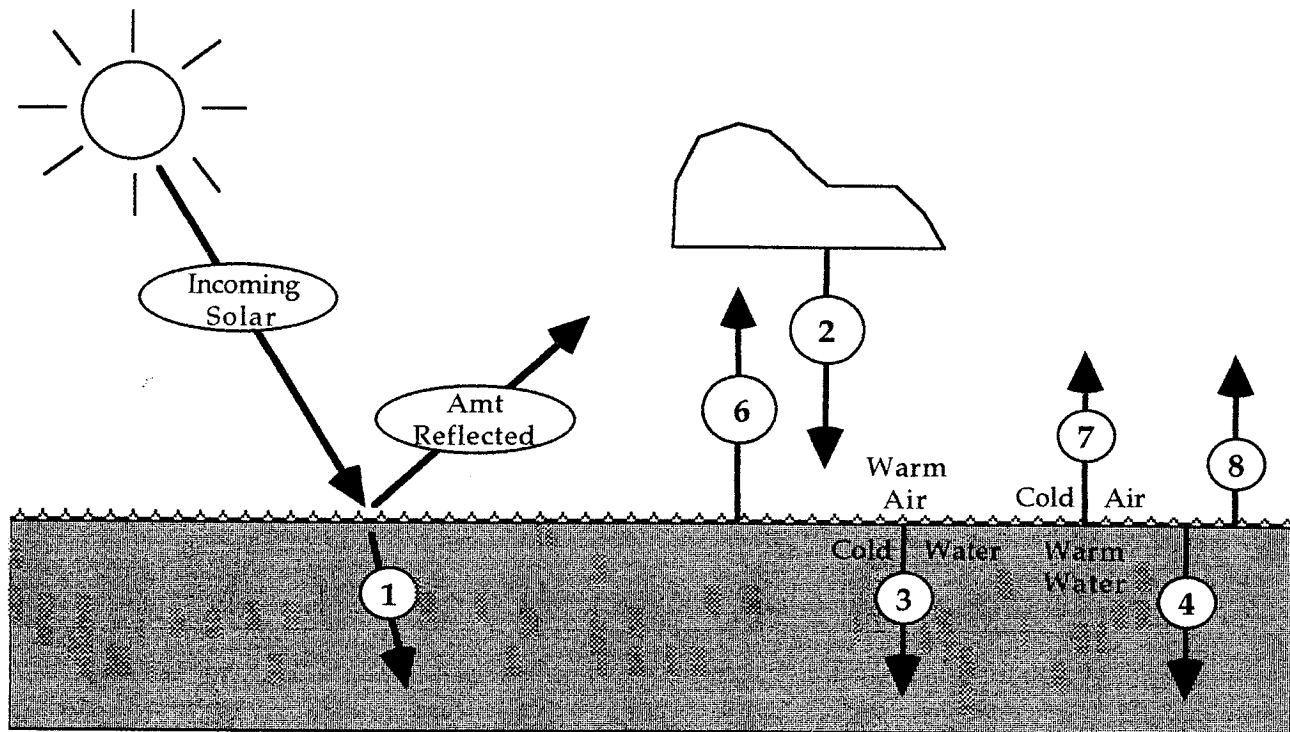


Figure 1. Components of the Surface Heat Budget.

In order for the global annual mean temperature of the earth to remain constant, the net effect must be such that the energy received from the sun (1) is balanced by a net loss of heat due to the other processes (2 - 9). However, this does not necessarily have to be valid on smaller spatial and temporal scales. If there is no balance, the sea surface will warm or cool. This warming or cooling can occur on daily, seasonal, or interannual time scales. For example, each hemisphere warms up during its summer because it receives more energy from the sun than it loses, and conversely, each hemisphere cools during its winter because it is losing more heat than it is receiving from the sun.

Global Mean Sea Surface Temperature Distribution

Figure () illustrates the distribution of the annual mean SST. The annual mean SST distribution approximately corresponds to the distribution of solar radiation received from the sun. They are both more uniform in the east-west direction and strongly vary in the north-south direction with highest values in the subtropics and lowest values at the poles. We will call this a zonal distribution of properties.

However, if we examine Figures () and () which show the monthly mean SST distribution in March and September, we see there are significant variations from the zonal distribution, particularly along the eastern and western

boundaries of the ocean basins. Therefore, there are other processes in addition to the incoming solar radiation which affect the SST distribution. These processes can have a significant influence on the SST on a wide variety of temporal and spatial scales. These processes include:

1. Movement of water by ocean currents
2. Movement of water by winds

Movement of Water by Ocean Currents

On an annual basis, the tropics receive more heat from the sun than they lose due to longwave radiation, conduction, or latent heat, while the poles lose more heat annually than they receive from the sun. If nothing else was happening, what would be happening at the tropics and poles? What is keeping the tropics from continually getting warmer and the poles cooler? The excess heat in the tropics must be transported to the poles by the atmosphere and ocean. Here, we will examine the transport of heat by the ocean currents.

Figure () illustrates the movement of water by ocean currents. In general, warm water is transported poleward from $\sim 25^\circ$ to $\sim 45^\circ$ in both hemispheres along the western boundary of each ocean basin, and cool water is transported equatorward along the eastern boundary of each ocean basin at these latitudes.

The net north-south circulation of water, then, acts to move warmer water from the tropics towards the poles where it is cooled, and cooler water from the poles towards the tropics where it is warmed. In this way, the ocean circulation then helps the global heat balance by removing excess heat from the tropics and adding heat to the polar regions. This north-south circulation of heat is seen in the global SST distribution as a northward displacement of isotherms on the western sides of ocean basins and a southward displacement of isotherms along the eastern sides (Figures () and ()).

Movement of Water by Winds

The Ekman Spiral - While frozen in sea ice in the 1890's, Fridtjof Nansen observed that icebergs, ice, and his ship were moving 45° to the right of the wind rather than with the wind. He asked a student, Vagn Walfrid Ekman to explain this. Ekman's theory considers the steady state balance of friction and the coriolis acceleration due to the earth's rotation. In this balance, the wind-driven surface current is 45° to the right of the wind in the Northern Hemisphere (to the left in the Southern Hemisphere), the wind-driven current decreases exponentially with depth, and it veers further to the right in the Northern Hemisphere (left in the Southern Hemisphere) with depth, forming the Ekman Spiral (Figure ()). The integrated net transport of the

wind-driven layer (the Ekman Spiral) is 90deg. to the right of the wind in the Northern Hemisphere (to the left in the Southern Hemisphere).

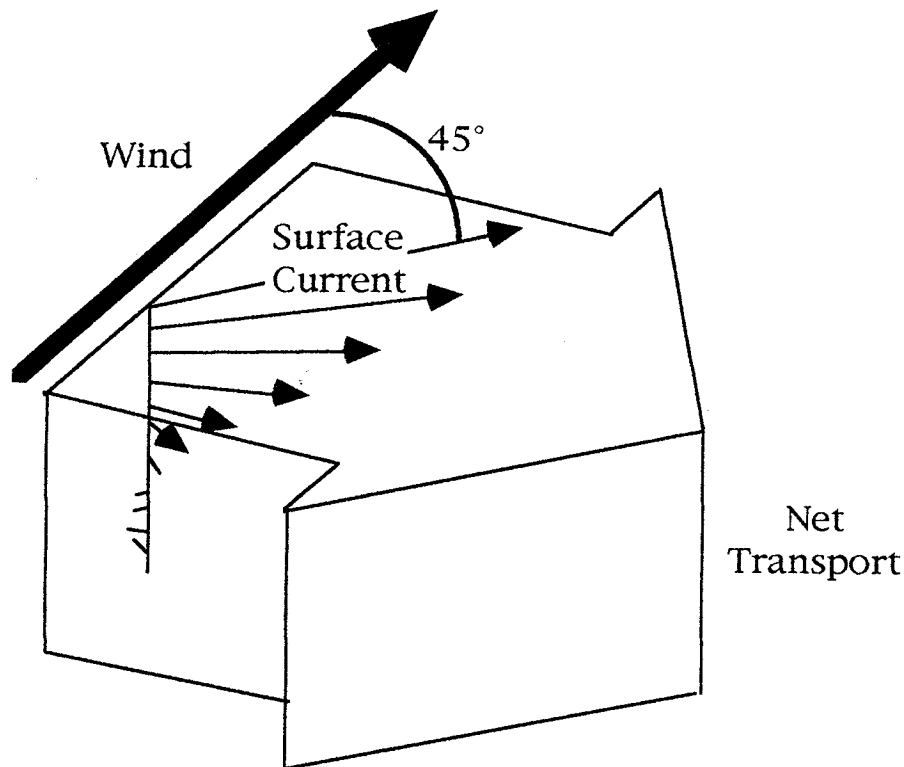


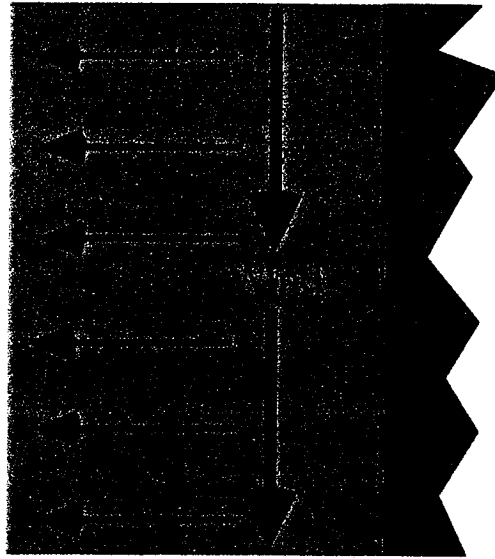
Figure (). The Ekman Spiral, redrawn from Introduction to Physical Oceanography by J. A. Knauss (1978)

This net mass transport of water creates vertical motions of water (upwelling or downwelling) in order to conserve mass.

Coastal, Wind-Driven Upwelling

When the winds along the west coasts of continents (eastern side of ocean basins) blow equatorward (from the north in northern hemisphere, from the south in the southern hemisphere), or have a component in this direction, there is a net off-shore movement of water in the wind-driven layer (divergence along the coast, Figure (), surface view). Deeper waters must move onshore and upward (upwelling) to replace the waters moving offshore (Figure (), side view).

Wind-Driven
Surface
Layer
Transport



West Coast of Northern Hemisphere Continent

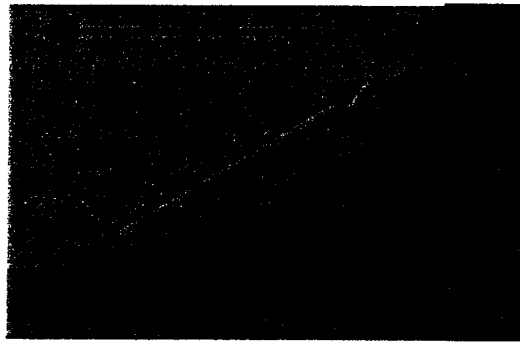


Figure (). Upwelling along the west coast of a Northern Hemisphere continent, redrawn from Introduction to Physical Oceanography by J. A. Knauss (1978)

Conversely, when the winds blow poleward or have a poleward component, there is a net on-shore movement of water in the wind-driven layer (convergence near the coast), and the surface waters must move downward (downwelling) near the coast.

Because the deeper waters are colder and higher in nutrient concentrations, the conditions that lead to upwelling cause colder surface temperatures and increased biological activity near the west coasts of the continents in both hemispheres.

Open Ocean Wind-Driven Upwelling Near the Equator

As shown in Figure (), the global surface wind patterns are such that the winds are from the northeast north of the equator and from the southeast south of the equator (dark arrows). The net movement of water in the wind-driven layer will be away from the equator both north (90 deg to the right of the winds) and south (90 deg to the left of the winds) of the equator (gray arrows). This divergence of surface waters near the equator leads to upwelling of colder (and higher in nutrient concentrations) subsurface waters.

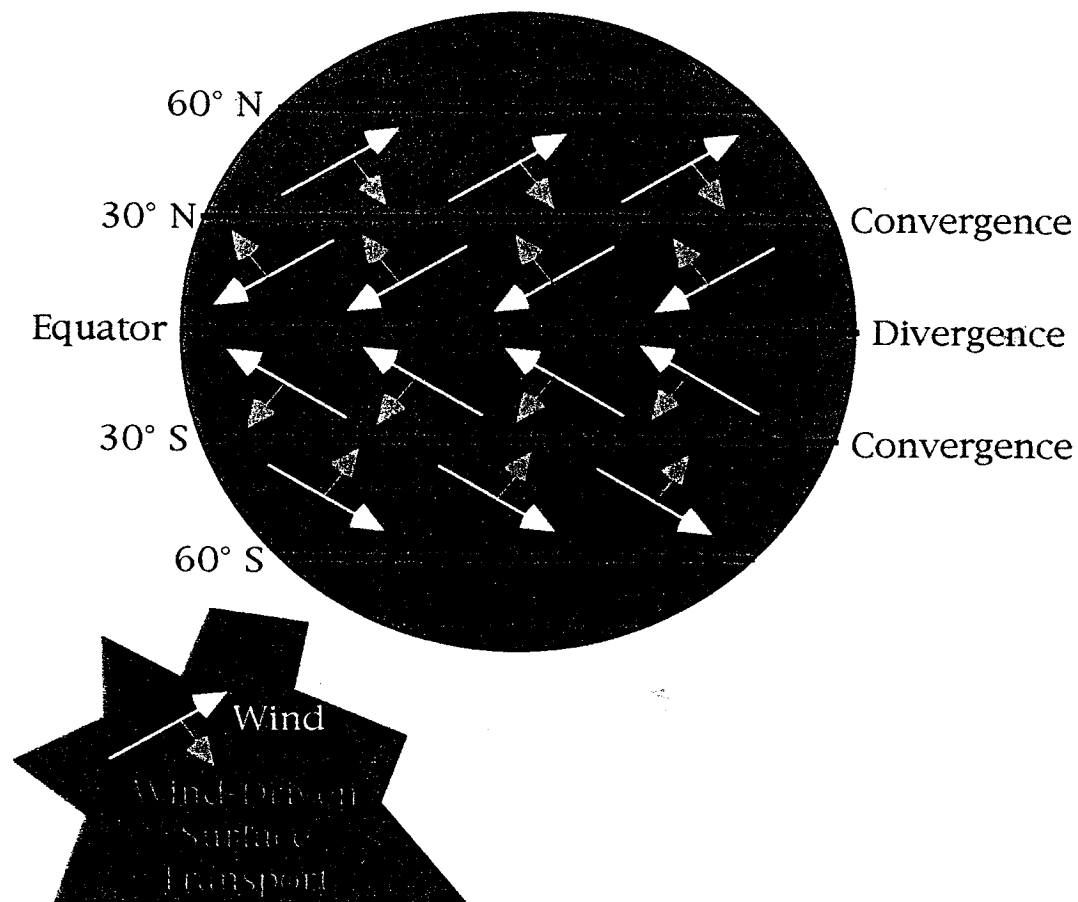


Figure (). Global surface wind patterns and the associated transport of water in the wind-driven Ekman layer.

Figure (). Wind-driven divergence along the equator, redrawn from Introduction to Physical Oceanography by J. A. Knauss (1978)

Diurnal Warming/Cooling

The amount of energy the surface receives from the sun (#1 in Figure 1) varies considerably on a daily basis. The surface receives heat from the sun only from sunrise to sunset, while it is continually losing heat due to longwave radiation, conduction, evaporation, and/or advection (#6-9 in Figure 1). As a result, the temperature of the sea surface can vary by as much as 0.5 deg C over a 24-hour period (Cornillon and Stramma, 1985). Certain conditions must exist in order to observe these sorts of daily SST differences, namely, clear skies (maximizes night-time cooling) and low wind speeds (minimizes vertically mixing). These small temperature differences are usually difficult to distinguish in satellite data without using more sophisticated data processing techniques than we will be using here.

Seasonal Warming/Cooling

The amount of energy the surface receives from the sun also varies considerably on seasonal time scales. This variation is due to the combination of the tilt of the earth on its axis of rotation and the orbit of the earth about the sun (Figure ()). The incoming solar radiation from the sun is less intense when a hemisphere is tilted away from the sun during its winter than when it is tilted towards the sun during its summer. As a result, in winter the surface receives less radiation from the sun than it loses to longwave radiation, conduction, evaporation, and/or advection, and its temperature decreases as a result. Conversely, the surface receives more heat from the sun than it loses, and its temperature increases, during each hemisphere's summer. Because the Southern Hemisphere is slightly closer to the sun in January (its summer) than the Northern Hemisphere in June, it will receive slightly more energy from the sun, but this difference is less than a 5% (reference?!).

The seasonal changes in SST are readily evident in satellite data (Figures () and ()). The greatest range in SST's occur in the subtropics, with the SST's near the equator and at the poles relatively constant throughout the year.

Include discussion on Monsoons here.

Interannual Variability

Perhaps the best known example of interannual variations in SST is the El Nino Southern Oscillation (ENSO) which occurs in the equatorial Pacific.

"Normal" Conditions in the Equatorial Pacific

Normally, the winds from the equator to ~30 deg N are from the northeast and are steady (the Northeast Trade Winds), while they are from the southeast and steady south of the equator to ~30 deg S (the Southeast Trade Winds). Since the coriolis affect is very weak near the equator, and non-

existent at the equator, the surface waters move westerly across the equatorial Pacific due to the NE and SE Trade Winds. As the waters move along the equator, they are heated by the sun. In addition, coastal upwelling is occurring in the eastern equatorial Pacific due to the wind-driven divergence of the surface waters near the continents. As a result, the "normal" equatorial SST distribution consists of the warmest SST's in the western equatorial Pacific and cooler SST's in the eastern equatorial Pacific. In addition, the height of the sea surface in the western Pacific is normally ____ cm higher than in the eastern Pacific (Reference ?!). This is due to a combination of the trade winds physically "piling" up the water in the west and the increased volume of the warmer waters.

Since the warmer SST's are associated with rising moist air, clouds and precipitation are closely associated with the pool of warm SST's in the western Pacific (the "Warm Pool").

El Nino Conditions in the Equatorial Pacific

In an El Nino event, the normally steady NE and SE Trade Winds weaken and/or shift direction. As a result, the "pile" of warm water in the western Pacific is allowed to propagate eastward. The arrival of the warmer waters in the eastern Pacific has several affects:

1. It increases the stratification of the surface waters as well as the depth of the colder, nutrient-rich subsurface waters. Because of this and the decreased strength of the Trade Winds, upwelling and biological activity in the coastal regions of the eastern Pacific is significantly diminished.
2. Therefore, the SST distribution of the equatorial Pacific during an El Nino event consists of a more uniform east-west distribution, with warmer than normal temperatures in the eastern Pacific.
3. The region of precipitation associated with the warm SST's moves eastward with the Warm Pool. Therefore, an El Nino event is characterized by increased precipitation in the eastern Pacific and drought conditions in the western Pacific.

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Determining SST from Infrared (AVHRR) Observations

Outline

- I. Radiation Principles
- II. Sources of Infrared Energy Received at the Satellite
- III. Atmospheric Absorption Windows in the IR
- IV. AVHRR Sensor
- VI. Atmospheric Sources of Error
- VII. Removing Atmospheric Influences

Radiation Principles

All objects whose temperature are greater than absolute zero emit electromagnetic radiation. This electromagnetic radiation is commonly called Thermal Emission.

The temperature of the radiating body determines the intensity and characteristics of the emitted radiation.

1. Hotter objects emit more total energy per unit area than colder objects (This is known as Stefan - Boltzmann's Law).
2. The hotter the radiating body, the shorter the wavelength of maximum radiation (This known as Wein's Displacement Law).

To visualize this, imagine an iron poker. At room temperature, it is black. Once it is put into a fire, it begins to glow red. This is because as its temperature increases, it is emitting electromagnetic radiation in the visible part of the spectrum. As its temperature continues to increase, it will appear yellow/white hot. This is because the wavelengths of its maximum emissions have moved from the longer red light to the shorter yellow light. Once the iron poker is removed from the fire, its color will become red again as its temperature decreases. As it cools further, it will return to its original black color. However, if you touch it now, it will still be warm. Again, as its temperature decreased, the wavelengths of its maximum emissions moved from the shorter visible light to the longer infrared wavelengths. At these wavelengths, we cannot see its emissions.

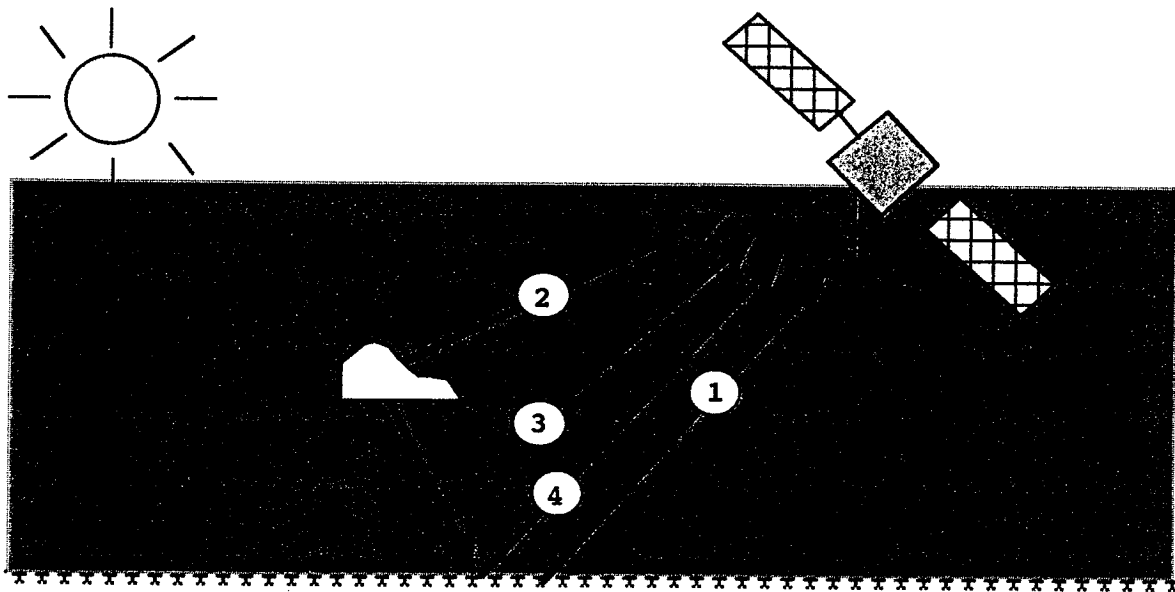
We can see our sun and its color is yellow because it is so hot (6000 K) that it emits most of its energy in the visible portion of the electromagnetic spectrum. Based on the earth's temperature (~300 K), MOST of the earth's emitted radiation (from land, the ocean, and clouds!) is in the longer THERMAL INFRARED (IR) portion of the electromagnetic spectrum. Although we cannot see this radiation (because our eyes only detect visible light), satellite sensors can measure the amount of radiation, and from the

amount of emitted radiation, infer the temperature of the land, ocean, and/or atmosphere.

Sources of Infrared Energy Received at the Satellite

Because the ocean, land, atmosphere, and clouds have relatively similar temperatures, all of these sources emit energy primarily in the infrared portion of the electromagnetic spectrum. Therefore, a satellite sensor used to determine temperature from measurements of infrared electromagnetic energy will actually receive this energy from several sources:

1. Surface (Skin) Emissions
2. Direct Cloud Emissions
3. Direct Atmospheric Emissions
4. Reflected Cloud / Atmosphere Emissions



We are interested in inferring sea surface temperature from measurements of the surface emissions of infrared electromagnetic energy. THE GOAL here, then, is to either minimize and/or correct for the energy arriving at the satellite from the other sources. We will look first at how to minimize the influence of emissions from atmospheric gases, then how to correct for clouds and other atmospheric influences.

Atmospheric Absorption Windows in the IR

Specific molecules absorb/emit radiation at specific wavelengths. There are four "windows" in the atmospheric absorption spectrum in which the atmosphere absorbs/emits little thermal infrared radiation based on the chemical composition of the atmosphere (the nitrogen, oxygen, and water vapor molecules):

1. 2.5 - 2.5 μm
2. 3.5 - 4.0 μm
3. 8.0 - 9.0 μm
4. 10 - 13 μm

If a satellite sensor operated in one of these "windows," there would be minimal absorption/emission by the gas molecules in the atmosphere, and surface thermal infrared emissions would be clearly visible from the satellite.

Advanced Very High Resolution Radiometer (AVHRR)

The AVHRR is one of several instruments on NOAA's operational polar-orbiting meteorological satellites. The AVHRR observes radiance from the earth at five wavelengths spanning the visible to thermal infrared portions of the spectrum (Table 1).

Table 1. AVHRR Wavelengths

Channel	Wavelength (mm)
1	0.58 - 0.68
2	0.72 - 1.10
3	3.55 - 3.93
4	10.3 - 11.3
5	11.5 - 12.5

Note that channels 3, 4, and 5 are in the infrared atmospheric windows and therefore can be used to observe the sea surface with minimal atmospheric interference, assuming cloud-free conditions.

Atmospheric Sources of Error

The accuracy of satellite sea surface temperature observations depends on the ability of radiometers to view the sea with little error introduced by the atmosphere. By operating in the atmospheric windows, the effect of the gas molecules in the atmosphere have been minimized. However, clouds, water vapor, and aerosols are additional sources of error in the atmosphere which must be considered.

Surface infrared energy cannot penetrate dense, widespread clouds. Therefore, in the presence of a thick cloud cover, the satellite sensor will measure the infrared radiation emitted from the clouds ONLY. Because clouds are typically several degrees colder than the surface, thick, dense, wide-spread clouds relatively obvious and easy to detect.

Thin clouds such as cirrus and very low stratus clouds are of major concern. They will lower the sea surface temperature measured by the satellite, but will not so much that the temperatures are obviously wrong. Cirrus clouds are really cold. Therefore, only a few small clouds can contribute large errors. Because they are thin, they are nearly invisible and difficult to detect. The problem is to detect their presence, and then correct or reject the erroneous measurements.

Water Vapor and aerosols attenuate the surface signal. Therefore, the signal arriving at the satellite in their presence must be corrected for. The problem with both water vapor and aerosols is that their concentration in the atmosphere is highly variable in both space and time.

The following table (taken from Stewart, Methods of Satellite Oceanography) shows the relative importance's of errors (in degrees Kelvin) introduced by various atmospheric sources:

3.7 μm band		10.5 μm band	
undetected clouds	0 - 10 K	undetected clouds	0 - 10 K
aerosols	0.3 - 5 K	water vapor	1 - 8 K
water vapor	0.3 - 1 K	aerosols	0.1 - 2 K
other gases	0.1 K	reflected sky	0.2 - 0.7 K
		other gases	0.1 K

Removing Atmospheric Influences

Again, sea surface temperature is inferred from the amount of infrared energy leaving the sea surface. The effect of the atmosphere is to attenuate this signal and to add other sources of infrared energy to the surface signal arriving at the satellite. These atmospheric effects must either be removed or corrected for in order to determine the surface temperature accurately from satellite measurements.

There are two steps to removing the influence of the atmosphere:

1. Detect and eliminate pixels containing clouds.
2. Once the cloud-free pixels are identified, the remaining pixels are corrected for the residual influences of water vapor.

Cloud Detection Methods

There are several possible methods/schemes to detect clouds:

1. Maximum Temperature - all observations of a small surface area over a relatively short period of time are compared, and the highest temperature is retained as the best estimate of temperature in that area. This method is based on:
 - a. Ocean surface features are more persistent than clouds.
 - b. Clouds are colder than the surface.This method works poorly for persistent, thin clouds.
2. Two Wavelength IR - compare temperature from 3.7 μm and 10.5 μm . If the temperatures are the same, then we can assume the measured signal came from:
 - a. the Sea Surface, OR,
 - b. Uniform Clouds, which will probably be detected in a visual image of the area of interest.If the temperatures at the two wavelengths are different, then there are scattered, undetected clouds in the scene.
3. IR Variability - temperatures of clouds tend to be much more variable in space than temperature of the sea surface. Therefore, all areas having a small deviation from a mean brightness temperature close to that expected of the sea in the region are accepted as good values.
4. Two Wavelength VIS-IR - uses reflected sunlight to detect clouds, on the assumption that the sea is much darker in visible wavelengths than clouds (because clouds are a better reflector of visible light than the sea surface!).

Once cloud-free pixels have been identified, the infrared radiance of the remaining pixels must be corrected for the influence of water vapor in the atmosphere in order to obtain accurate values for SST.

Water Vapor Corrections -

There are two methods to correct the signal arriving at the satellite for the effects of water vapor:

1. Single-Wavelength Corrections - Many instruments use only a single IR wavelength, usually 10.5 μm . Therefore, there is no independent information for estimating the influence of water vapor available from the spacecraft. In this case, climatological estimates of water vapor or regional radiosonde observations must be used.
2. Two-Wavelength Corrections - Because radiation at 10.5 μm is much more sensitive to water vapor than radiation at 3.7 μm , the 10.5 μm measurements can be used to correct the 3.7 μm measurements. The

difference in temperature at the two wavelengths is used to estimate the correction for the influence of water vapor.

Once the atmospheric influences are removed/corrected, the SST can be inferred from the amount of infrared radiation arriving at the satellite from the surface because hotter objects emit more energy per unit area than colder objects (Stefan-Boltzman's Law).

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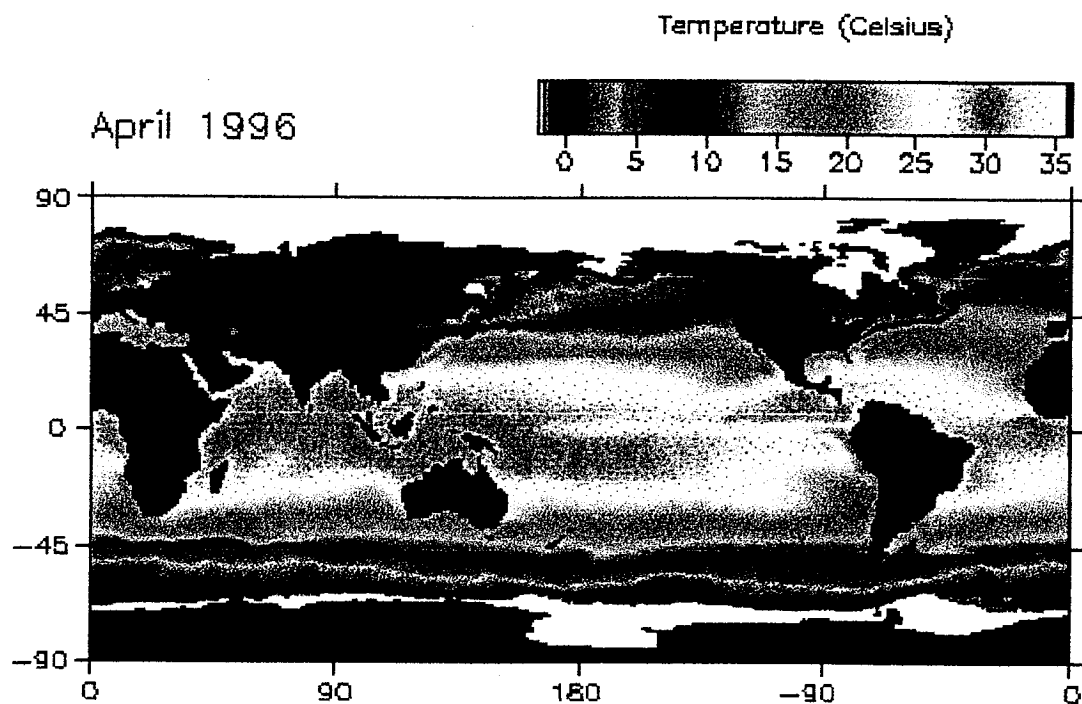
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STUDYING THE EARTH'S ENVIRONMENT FROM SPACE: Ocean Circulation and Sea Surface Temperature



Macintosh Computer Laboratory Exercises

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Making Observations of the Seasonal Warming and Cooling of the Hemispheres Using Sea Surface Temperature (SST) Data from Satellites and Buoys

{Words and phrases which are in **bold** will be included in a glossary.}

The seasons are an example of the **natural variation** of the earth/sun system. On the other hand, the dramatic warming of the eastern tropical Pacific Ocean during an El Nino is an example of an unusual or **anomalous variation** in the SST of the oceans. One reason scientists study the annual and interannual variability of the oceans and atmospheres is to identify and examine anomalous events like El Nino, which may be due to some natural or human-induced forcing and which may cause severe weather patterns worldwide.

SST is an important parameter for monitoring climate change and periodic phenomena like El Nino. A global increase of SST may be an indicator of global warming, and the change in its geographical distribution (which is what happens during an El Nino) can be a sensitive indicator of climate change.

In these exercises, you will use actual research data of the oceans to study the:

- ◆ Geographical distribution of the sea surface temperature (SST) around the earth.
- ◆ Seasons, or seasonal cycle (also called the annual cycle) as expressed in the SST.
- ◆ Year-to-year variability, also known as the **interannual** cycle, of SST.
- ◆ Onset of the current El Nino in the eastern Equatorial Pacific Ocean.
- ◆ How the SST during an El Nino varies from "normal" SST conditions.

The data set you will be using for these exercises is comprised of **gridded**, monthly averaged SST measurements from both space-borne instruments and ocean buoys. The satellite measurements used in this data set are derived from the **Advanced Very High Resolution Radiometer (AVHRR)** aboard the **NOAA Polar Orbiting satellites**. These data are produced as a **real-time** global SST analysis by Dr. Richard Reynolds from the Climate Modeling Branch of the National Centers for Environmental Prediction of the National Oceanic and Atmospheric Administration (NOAA). They cover the period from 1982 - 1997, and contain monthly averages of SST (hence, there are 192 monthly files).

These exercises are inquiry-based and designed for advanced high school or introductory-level undergraduate earth science classes and laboratories. Information useful for answering the following questions can be found in the associated series of [Ocean Circulation Lectures](#) (under development). Additional background is in the sections [Information on Satellite-derived Sea Surface Temperature Measurements](#) and [Information on the Global Monthly Sea Surface Temperature Data Set](#) (both under development).

BEFORE YOU BEGIN THESE EXERCISES...

Before you begin to work on these exercises you will need the following items:

1. SEE-Image (a version of NIH-Image) installed and configured.

2. Global Monthly Sea Surface Temperature Data Set for 1982-1997 (from the folder titled, Global SST' on the CD-ROM or your computer's hard drive).

3. A copy of these exercises

4. Access to the:

SEE-Image Tutorial

Ocean Circulation Lecture Set

Information on Satellite-derived Sea Surface Temperature Measurements

Information on the Global Monthly Sea Surface Temperature Data Set

SEE-Image Software

SEE-Image is a modified version of NIH-Image. To use the various functions necessary for the exercises, SEE-Image must be configured properly. If you are unfamiliar with SEE-Image, please work through the step-by-step tutorial. If you are familiar with NIH or SEE-Image and do not need the complete tutorial, please refer to the beginning of the SEE-Image Tutorial to configure your system and have proper macros loaded before beginning the exercises.

The SEE Image Tutorial may also serve as a reference manual for processing images for incorporation into another document or for exporting data into another application. It provides more detailed instruction for some operations than are found in the exercises.

LIST OF EXERCISES

EXERCISE 1 Investigating the characteristics of the **Global Monthly Sea Surface Temperature Data Set for 1982-1997**

EXERCISE 2 Observations of the geographic, or spatial, variation of SST

EXERCISE 3 Observations of the seasonal variation of SST

EXERCISE 4 Observations of the year-to-year, or inter-annual, variation of SST

EXERCISE 1 - Investigating the characteristics of the Global Monthly Sea Surface Temperature Data Set for 1982-1997

Before working with any data it is important to understand the characteristics of the data. A knowledge of the file naming convention, data type, geophysical units, data source, and temporal and spatial resolution are critical to ensure correct scientific interpretation. Equally as important as the data is the software available to read and display the data. You will be using SEE IMAGE.

Characteristics of the Global Monthly Sea Surface Temperature Data Set for 1982-1997

Geophysical Measurement:	Sea Surface Temperature
Units of Measurement:	Degrees Celsius
Source of Data:	Satellites (NOAA AVHRR) and various buoys
Temporal Resolution:	Monthly averages
Spatial Resolution:	1 degree latitude x 1 degree longitude
Software:	SEE Image

In this activity you will learn how the SST data files have been named and how to open and display the data files as images using SEE Image, and how to apply a color table to the image.

A. Opening and displaying a global, monthly SST data file

These SST data contain monthly averaged values of SST in degrees Celsius over the entire earth, excluding land, on a 1-degree latitude by 1-degree longitude grid. Each file is named according the year and month over which the data were collected and averaged. The file names are constructed as follows:

19YYMM.tif

where:

YY = last two digits of the year (from 82-97)

MM = two digits representing the month (from 01-12) where
01=January, 02=February, etc.

1. First, launch SEE-Image, by double-clicking on its icon.

2. Then, open a data file from any year within the OISST folder on the CD-ROM by selecting File/Import.

You should see an image which looks like a rectangular map of the earth, in shades of gray.

Interpret the filename and record for which year and month you opened an SST image?
Month _____ Year _____

B. Adding color to the image

To better distinguish differences in SST around the oceans we can apply color to the image using a color table, or look-up table (LUT), that assigns values of SST to each color.

1. Select Options / Color Tables / SST

The image should now be displayed in color and the LUT window will display the color range used. Notice the LUT window corresponds to the color legend on the image. This legend associates the color of the **pixels** in the image to their temperature.

Move the cursor over the LUT window and look at the number associated with "Value" in the Info window. These are the pixel values associated with each color. The images are stored as byte data ($2^8 = 256 = 1$ byte) with pixel values, also called Data Numbers (DN), between 0 and 255. This is a way to store data compactly. As you move your cursor around in the image, using the mouse to move the cursor, the INFO box shows you the x and y coordinates (and, in a future version) latitudes/longitudes of the image and the pixel value or DN ("Value" in the INFO box). The relationship between these pixel values and the actual SST values is examined through the following questions:

What pixel value is associated with black? _____ What is represented by these pixel values?

What pixel value is associated with white? _____ What is represented by these pixel values?

What is the relationship between pixel values (DN)
and corresponding SST values (in oC)?

Use the following relationship to convert from DN to SST:

$$\text{SST(oC)} = 0.15 * \text{DN} - 1.79$$

For the range of DNs of 0 to 255, what is the corresponding range of SST's?

You may also simply read the temperature from the color bar legend provided on the image.

Move your cursor over regions of land and ice in the image and study the values in the Info window. Move your cursor all around the image now, and answer the following question:

What is the approximate range of temperature values displayed in this image and where in the oceans are the coolest and the warmest SSTs?

Range:

Coolest: DN = _____

SST = _____ °C

Color = _____

Location:

Warmest: DN = _____

SST = _____ °C

Color = _____

Location:

C. Using SEE-Image to Calibrate the DN Values to SST in Degrees Celsius

SEE-Image lets you **calibrate** the pixels values of an image with known SST values. Please go through the following calibration exercise now so you will be familiar with it for later explorations.

1. Choose File/Import to open any monthly image file you like.
2. Choose Analyze/Reset to eliminate any previous measurements. Drag the Info window into view.
3. Choose Analyze/Options....choose only Mean Density. Mean Density calculates the average pixel value in a selected area when you measure.
4. Choose the rectangular selection tool from the Tools window and draw a tiny rectangle (about 1 pixel by 1 pixel) on the image near the equator where the SST is near its maximum.
5. Choose Analyze/Measure.
6. Make two more 1x1 rectangular sections in other parts of the image (choose a very cool region and a region of moderate temperature), choosing Analyse/Measure after each one. Be sure not to include any of the image annotations or land in your small selections.
7. Choose Analyze/Show Results.
8. Now, either using the algebraic relationship between SST and pixel value ($SST(^{\circ}C) = 0.15 * DN - 1.79$) or by reading the SST values from the color bar on the image itself, write down the SST associated with each of the pixel values in the Mean column of the Results window. Here is a table to help you:

Mean Pixel Value	SST (°C)

9. Choose Analyze/Calibrate....

10. In the dialog box, select Straight Line and type in 'degrees Celsius' for the Unit of Measure.

11. Type in the three Known SST values (from the table above) in the second column of the table in the dialog box. Click OK.

Now, move your cursor around in the image, and watch the Info Box. You will see the actual SST displayed for each pixel.

Hint: Once an image has been calibrated, an open diamond appears to the right of the filename across the top of the image.

If you will be working with many images during a given session (which is the case for many of these exercises), calibrate the first one you open at the beginning of the session. All subsequent images will then be calibrated and you'll know that they are by the presence of the open diamond (in a stack, the open diamond appears to the left of the filename).

Likewise, if you will be working with a series of images in a stack, first create the stack, then calibrate the first image in the stack and the rest will automatically be calibrated.

D. Studying how the data are organized geographically

Now study the latitude and longitude annotations on the image. North latitudes are always positive and south latitudes are always negative. These images are centered on the Equator (0 degrees latitude) and the International Date Line (180 degrees longitude). Longitudes are referenced to the Greenwich Meridian (0 degrees longitude) with longitudes to the east of 0 degrees being positive and longitudes to the west being negative. Answer some general questions to get familiar with the geographic layout of the image:

Locate the center of the image and record the SST at that location. To do this, use the tool which draws a straight line (next to the paint brush tool), draw a line along the International Date Line on the image from North to South. Draw another line along the Equator. Record the SST in degrees C, at the approximate intersection of these lines. You can "write" the SST directly on the image by using the text tool (the letter A in the tools window.) and typing.

Similarly, locate and record SST at the intersection of the Greenwich Meridian and the Equator.

Using the text tool, label north and south latitudes, and east and west longitudes directly on the image.

E. Studying Data Resolution

1. Select the line drawing tool from the Tools window.
2. Draw a horizontal line from the left edge of the image to the right edge (holding down the shift key will force the line to be straight). While drawing the line, the

Info box display DX (the change in the X direction) and DY (the change in the Y direction).

3. Record DX once you have drawn the line all the way across the image.

How many pixels wide is the image?

How many data points (also called pixels) are there per degree of longitude?

Repeat steps 1. – 3. Above except draw the line from the top of the image to the bottom of the image and record DY.

How many pixels high is the image?

How many data points (pixels) are there per degree of latitude?

The images in this data set have a **spatial resolution** of _____ latitude by _____ longitude.

Some characteristics of earth observing satellites make it difficult to interpret the data without some considerable manipulation. One such characteristic is the inability of the thermal-infrared sensor called the AVHRR to “see” the ocean’s surface in the presence of clouds. For this reason, and to reduce the overall data volume, you will use monthly averaged images in these exercises. It is useful, however, to consider a satellite image of the ocean’s surface temperature for a single day.

1. Open the file ‘daily94jul1.tif’, and apply the SST LUT to it.

What colors represent land and missing data (clouds) in this image?

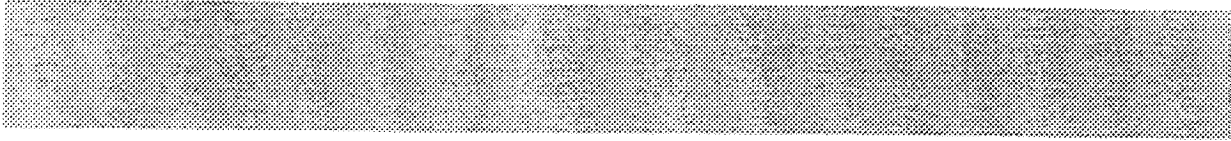
Land: _____

Clouds: _____

% cloud cover: _____

Discuss the benefits and drawbacks of monitoring the ocean temperature using daily images such as this one.

Discuss the benefits and drawbacks of monitoring the ocean temperature using monthly images.



{When this section is complete, it will include a discussion about image resolution with examples of nice, high resolution imagery. The questions will be designed to help students understand the concepts of data resolution and the appropriateness of certain data types for certain kinds of studies.}

2. Close this image.

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EXERCISE 2 Observations of the geographic, or spatial, variation of SST

A. What determines where the ocean is warm and cold?

You have learned that, on an annual basis, solar heating is greatest near the earth's equator and least near the earth's poles. To convince yourself of this, study the image of annual solar radiation from the Earth Radiation Budget Experiment (ERBE) for 1987, which can be found in the folder called MISC FILES.

5. Select File/Open and locate the file called, 'erbe_insolation_87.tif'.

Based on this figure, where would you expect to find the highest temperature waters in the ocean? The lowest temperature waters?

To check your answer on the above question, study the image of the average annual SST for 1987, a representative year, by opening the image called '1987avg.tif'. Are you right?

Were there any regions where your hypotheses were incorrect?

B. Observing the Geographic Distribution of SST

You will continue your exploration of the geographic variations of SST by studying one monthly SST image from the **Global Monthly Sea Surface Temperature Data Set for 1982-1997** using the DENSITY SLICE TOOL in SEE-Image.

1. Open a global SST image for any month you would like (March and September would be good choices) from the folder titled, 'Global SST'. Apply the SST color table to this image.
2. Select the density slice tool by double - clicking on the LUT tool (horizontal line with an up and down arrow) in the 'Tools' window. This will put a solid block of color (default color is red) on the 'LUT' window.
3. To change the color of the solid block, select the eye - dropper and then double click on the color block in the LUT. This will bring up a color wheel. Click on the middle portion of the color wheel. The window will now display gray as the "New" color. Select "OK". Now the color block (and the paint brush) in the 'LUT' should be gray.
4. Double - click again on the "LUT" tool to reactivate the density slice option. Click and hold on the upper line of the color block and drag it to so the 'Upper' value in the 'Info' window is 180. Next, click on the lower line and drag it so the "Lower" value in the "Info" window is 146. The width of the color block now corresponds to approximately 5°C. Verify this by looking at the gray color block on the color legend on the image. Move the color block so that the corresponding block on the color legend

(on the image itself) falls between 20° and 25°. In the image you will see that all SST values in the image which fall in the 20° - 25° are now colored gray.

5. In the LUT window, click and drag the gray block to the top of the color bar and then slowly drag it toward the bottom. As you drag the density slice region down the color bar you will highlight regions with similar SST values in the image. While you are holding down the mouse and moving the color bar the range of values (upper and lower limits) highlighted will be displayed in the Info window and on the color legend. Do this several times.

Now you can answer some questions about the distribution of SST around the earth.

Use the density slice tool to highlight the warmest SSTs (between about 25° and 30°). Where do the warmest SSTs occur? Why?

Now do the same thing for the coolest SSTs (between about 0° and 5°). Describe the distribution of SST in this range for the Southern Hemisphere? For the Northern Hemisphere?

Study the geography of the Southern Hemisphere and describe a unique feature of the southern high latitudes which might have an effect on the SST. How do high latitude regions in the Northern Hemisphere differ in this respect from high latitude regions in the Southern Hemisphere?

You will now use another of SEE-Images analysis tools to observe, in a more quantitative way, how SST varies long lines of similar latitude (**zonal variation**) and longitude (**meridional variation**). The tool you will use is called the PLOT PROFILE tool.

1. First, create plots with fixed axes scales by selecting Options/Profile Plot Options, and click on the box for 'Fixed y-axis scale'. Enter 0 for minimum and 255 for maximum. Click OK.
2. Select the Plot Profile tool by clicking on it. Draw a line on the image, from west to east at 45° South latitude. HINT: To draw a straight line, hold down the SHIFT key while drawing the line. When you release the mouse button, a new window will appear with the plot of SST as a function of distance on the image along the zonal line you drew at 45°S.
3. Save the resulting plot in a new file by following the following steps:

Edit/Copy Plot
File/New
Edit/Paste

4. Using the text tool, annotate this plot with the month and year, and the latitude along which this zonal plot was created.

5. Now do the same thing as in step 2 but draw the profile along a line of constant longitude, or **meridian** (try 170°W).

6. Paste this plot in the same file as the zonal plot using the following steps:

Edit/Copy Plot
Edit/Paste

7. Annotate the plot as in step 4 and answer the following questions.

Study the two plots you just made. In general, how does SST vary along lines of similar latitude? Longitude?

Is this what you expect? Why?

What is the basis for this distribution of SST?

Locate two regions on the image you have opened where the SST does not follow a distinct latitudinal or zonal pattern.

Describe where this region is relative to the nearest land mass.

Region 1:

Region 2:

Open the ocean currents map in SEE Image (ocean_currents.tif) and describe the ocean currents for the two regions you have named above.

Region 1:

Region 2:

If, in an average year, the tropics receive more heat from the sun than they lose, and the poles lose more heat than they receive from the sun, what is preventing these regions from just continuing to heat up and cool off, respectively, until they are uninhabitable? Study the map of ocean currents and the image of SST you have been working with, to describe a mechanism to answer this question.

7. Close all images.

EXERCISE 3 Observation of the seasonal variation of SST

This exercise has five sections. In the first three sections, you will use some of SEE Image's tools to explore the SST data in a **qualitative** sense, to observe how SST varies with the seasons. First, you will use a familiar SEE Image tool, the density slice, to observe the temporal variability from month to month. Next, you will learn how to create a movie of the monthly images, called an animation. Finally, you will create a montage of the twelve monthly images to observe SST changes throughout the seasons. The final two sections of this exercise will hone your **quantitative** skills in analyzing the data. You will use IMAGE MATH in SEE Image to compute the difference between two images, and you will create and plot a time-series of SST.

A. Prepare the Data

1. Insert the SST CD-ROM Vol. 1 into your CD-ROM drive and open it. Navigate to the 'GLOBAL SST' data folder. Select one year and open all twelve monthly SST images for that year.
2. Select Stacks/Windows to Stack to put all twelve months in a stack. Use the > key (also the period key) to move forward through the stack and the < key (also the comma key) to move backwards through the stack
3. Choose Options/Preferences and select Display Slice Titles Only. This will result in the display of the file names, across the top of the stack, when you move through the images in the stack with the > and < keys.
4. Calibrate the top image in the stack. An open diamond is displayed to the left of the file name in the title bar of the stack when the images have been calibrated.

B. Color the Images with the Same LUT

1. Select Options/Color Tables/SST to display the images in the stack in color.

C. Use the Density Slice Tool to Observe Monthly Changes in SST

To begin your observations of how SST changes with time throughout a year, use the DENSITY SLICE TOOL, as you did in Exercise 2, section B. This tool allows you to identify a range of temperatures with a contrasting color and step through the images in the stack superimposing the same temperature range on each image.

1. Position the stack with the January image on top.
2. Follow the instructions in Exercise 2B(1-5), to select and configure the density slice tool.
3. Move the density slice in the LUT window until it corresponds to the warmest temperatures on the image's color bar (between 28oC -32oC).
4. Using the > key, move slowly through the images in the stack, a month at a time and watch what happens to the range of SSTs you have highlighted with the density slice tool.

Describe what happens to the warm SSTs as you advance through the monthly images.

5. Position the stack with the January image on top once again and this time move the density slice tool until it corresponds to the coolest temperatures on the image's color bar (between about 20C - 70C). Repeat step 4.

Describe what happens to the cool SSTs in each Hemisphere.

Study the cool SSTs in the Southern Oceans. Is there much zonal variation in SST from month to month in this region? Comment on the variation you observe in the southern, high latitudes as compared to the same SST range in the northern, high latitudes.

What's the explanation for what you observe?

D. Investigating SST Seasonal Variations from an Animation

A technique commonly used by scientists to visualize data collected over time is called **animation**. Each image in the stack is displayed automatically, and in sequence, to give the impression of a movie.

1. Choose Stacks/Animate to animate this stack. Use the number keys from 1 to 9 to control the speed. To stop the animation, click anywhere on the image.

Describe what you see. Does this technique of animating the monthly SST images bring anything new to light in your study of the seasonal variation of SST?

Pay attention to western boundaries, especially in the North Atlantic and the North Pacific. Describe the SST variability in these regions?

E. Investigating SST Seasonal Variations from a Montage

1. Select Stacks/Make Montage.
2. Enter 3 for columns, 4 for rows, 1 for increment and leave the rest at the default.

Study the images in the montage concentrating first on the Northern Hemisphere and then on the Southern Hemisphere. To make this a little easier, follow these steps:

3. Use the rectangular selection tool to select the entire Southern Hemisphere from the top row of images. Cut the selection. Do this for each row of images in the montage. Now study the SST in the Northern Hemisphere as the months progress.

In what months are SSTs warmest in the Northern Hemisphere?

Where do the warmest SSTs occur in the Northern Hemisphere and what are the approximate values?

In what months are SSTs coolest in the Northern Hemisphere?

Where do the coolest SSTs occur in the Northern Hemisphere and what are the approximate values?

4. Save this montage as Northern_montage.
5. Create a new montage to study the Southern Hemisphere SSTs by selecting Stacks/Make Montage
6. Enter 3 for columns, 4 for rows, 1 for increment and leave the rest at the default.
7. Use the rectangular selection tool once again to select the Northern Hemisphere from each row of the montage. Cut the selection from each row.

In what months are SSTs warmest in the Southern Hemisphere?

Where do the warmest SSTs occur in the Southern Hemisphere and what are the approximate values?

In what months are SSTs coolest in the Southern Hemisphere?

Where do the coolest SSTs occur in the Southern Hemisphere and what are the approximate values?

8. Save this montage as Southern_montage.

9. Close the montages and the stack.

F. Using SEE Image Math to Observe the Seasonal Variation in SST

Another type of analysis used to see how data change with time is to simply subtract one image from another.

1. Open one image for March and apply the SST color table if necessary.

2. Calibrate the image (See Exercise 1(C)).

3. Open the September image for the same year. Make sure the image is calibrated by checking for the open diamond to the right of the filename.

3. Select Process/Image Math.

4. Select the files such that the March image is subtracted from the September image. Select (* 1.) and (+0.).

5. Since the images are calibrated, select “real result”.

Use the cursor to move around the resulting image checking the values in the “Info Box”. Enhance the image to make it easier to see the regions of largest difference.

What does it mean when the differences are positive? Negative?

Where in the oceans are the differences between March SST and September SST positive? Why?

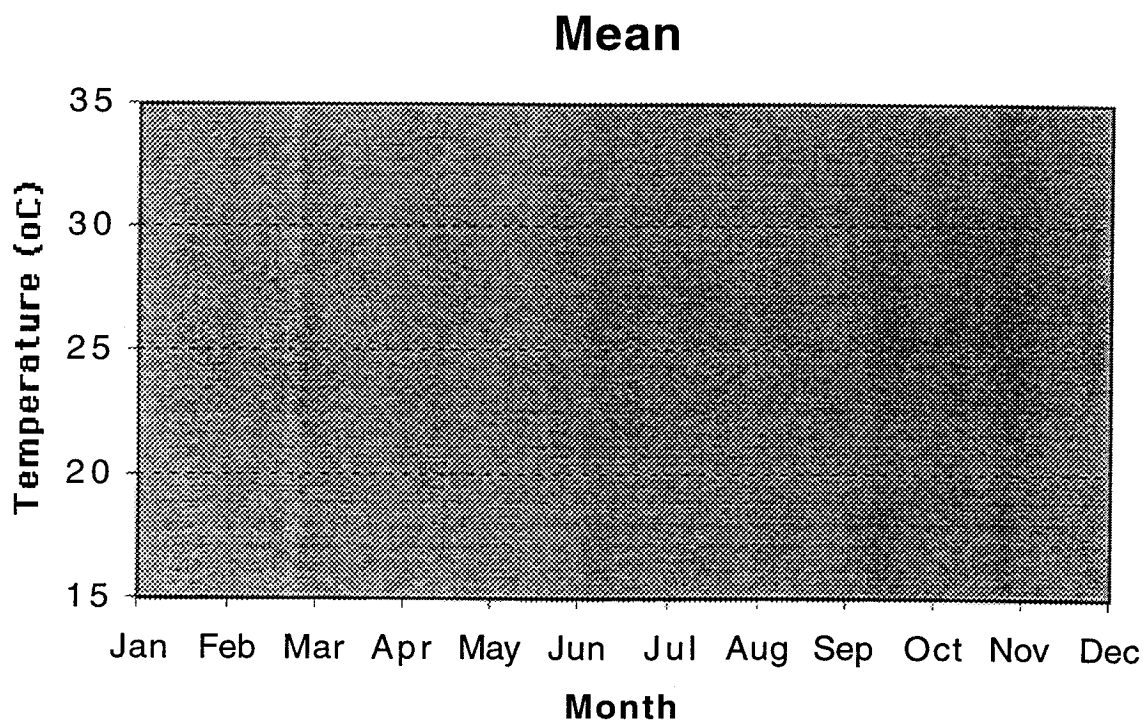
Where in the oceans are these differences negative? Why?

G. Creation of a Time-Series of SST to Observe Seasonal Variations

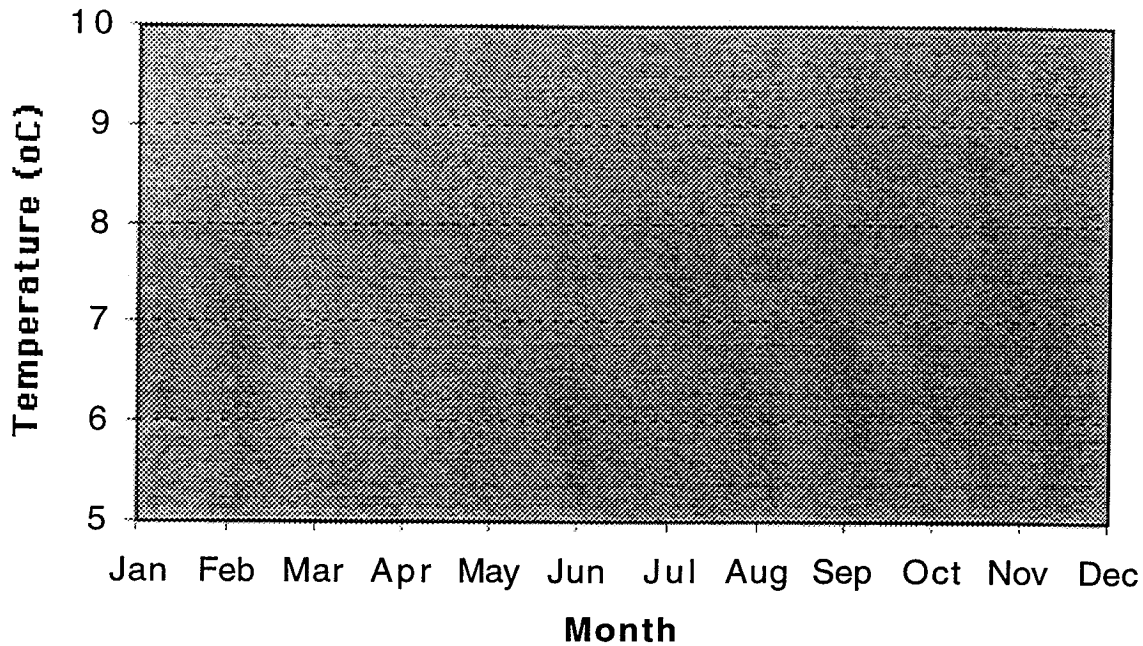
You will now perform some analysis on the monthly SST data which is identical to analyses performed by scientists in their research in order to study the temporal variation of a geophysical parameter. You will use SEE-Image to compute the average SST in a Northern Hemisphere ocean basin for each month, and create a plot of the SST as a function of month. You will do the same thing for a Southern Hemisphere Ocean basin. Comparing the two plots will make clear how the seasons affect SST.

1. As above, open twelve monthly images for 1994.
2. Create a stack of the twelve monthly images and apply the SST color table to it.
3. Calibrate the first image in the stack using the technique described in Exercise 1(C).
4. Draw a solid line across the first image in the stack (which should be January) at the Equator.
5. Choose the freehand selection tool from the tool bar.
6. Select the entire North Pacific Ocean, coming as close the line drawn at the Equator as you can (but DO NOT include that line in your selection).
7. Choose Analyze/Reset to clear all measurements.
8. Choose Analyze/Options and select mean and standard deviation.
9. Choose Analyze/Show Results to see the Results window on your screen and position this window so you can see both the images and the results windows.
10. Choose Analyze/Measure.
You will see the mean and standard deviation appear in the Results window, for the region you have selected on the January image.
11. Use the > key to move to the next window (February) in the stack and notice that your selection automatically appears on this image.
12. Choose Analyze/Measure (or apple1). There are now two measurements in the Results window; one for each month.
13. Use the > key to move through the stack one month at a time, computing the mean and standard deviation for each month by choosing the Analyze/Measure command or apple1.
14. Once you have done this for all twelve months, save the Results window (File/Save As) as North_Pac_97(measurements).
15. Use the < key to position the January image on top once again.
16. Using the free hand selection tool, select a region in the South Pacific Ocean which is similar in size to the region you selected in the North Pacific. DO NOT select the line you have drawn over the equator.

17. Choose Analyze/Reset, and then compute the mean and standard deviation of this region by choosing Analyze/Measure. You should now see one measurement in the Results window.
18. Using the > key to advance one image at a time through the stack, and the Analyze/Measure command to compute the statistics, do this for all twelve months.
19. Save these results as South_Pac_97(measurements).
20. Open the two results files and type in the name of the month in place of the 0.00 in the first column, for each row of measurements.
21. Now, create two plots of these data either by hand (use the figures below to guide you) or using a plotting package you have access to. For the first one, plot month on the x-axis and the mean SST on the y-axis for both the North Pacific and South Pacific (one set of axes, with two plots of mean SST). The second plot should also have month plotted on the x-axis. The y-axis of this plot should be the standard deviation for the North Pacific and the South Pacific.



Standard Deviation



Write a discussion interpreting the plots, including reasons for the trends and magnitudes of the curves.

Here's an idea for additional exploration of the seasonal variability in SST;

Select other regions of the world's oceans, create time-series as described above, and then discuss the reasons for the variation in the seasonal cycle among regions.

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EXERCISE 4 Observation of the year-to-year, or interannual, variation of SST

A. Qualitative Observations of Long-term Interannual Variability

1. Locate the folder labeled "Decembers" on your hard disk.
2. Choose File/Import and check 'open all' in the dialog box to open all the December images for all sixteen years from 1982-1997.
3. Choose Options/Color Table/SST to apply a color palette to the top image .
4. Choose Options/Propagate/Look-Up Table to apply this color table to all opened images.

Steps 5 and 6 will create a stack containing all of the December images, with the filenames displayed on each image in the stack:

5. Choose Options/Preferences and click on 'Display slice titles only'
6. Choose Stacks/Windows to Stack to create a stack with the filenames displayed.

Using the tools in SEE-Image which you are familiar with from the first three exercises, explore the long-term variation of the global SST and record your observations. Here are some suggestions for your exploration:

Start by simply moving through the stack one image at a time using the < and > keys (these are also the comma and period keys, respectively) until you are familiar with the data and can record some general comments about the SST throughout the sixteen year period.

Use the density slice tool (Exercise 2(B)) to highlight the warmest (coolest) SSTs and observe how they vary throughout the years. Are there any years which appear warmer (cooler) than others, on average?

Create a montage from the images in the stack and use the selection and drawing tools to isolate regions (the Equatorial Pacific is a good region to look at) in order to make it easier to compare them visually (see Exercise 3(D)). Remember, a selection made on the top image in the stack automatically appears on every image in the stack when it is displayed.

7. Choose/Stacks/Make Montage... and enter the following information in the dialog box:

Columns: 4
Rows: 4 (2, if you want to look at the first 8 years initially)
Scale Factor: 0
First Slice: 1
Last Slice: 16 (8, if you want to look at the first 8 years initially)
Increment: 1
Check "Borders".
Do not check "Number Slices".
Click "OK".

It might be easier to look at just 8 years at a time in the montage (modify the Rows and Last Slice information in the Montage dialog box as shown above). Record your observations.

If you drew lines on the images in the Montage, or altered them by cutting out sections, now is the time to close this montage and work again with the original stack of 16 December images.

Finally, create a movie of the 16 years and record anything new you observe.

8. Choose Stacks/Animate.

Which years look anomalous? Why? Which SEE-Image tool(s) make it easier for you to observe the anomalous data? Can you make some general comments about long-term oceanographic variability of SST?

B. Quantitative Observations of Long-term Interannual Variability in the Eastern Equatorial Pacific Ocean

As you probably figured out, even though the eye is a very sensitive instrument, it is hard to observe very subtle changes in SST from year-to-year. That is why scientists also use quantitative techniques involving statistics and the creation of time-series to discern such changes. You will now create some time-series of mean SST and standard deviation, for a very interesting region of the earth's oceans, the Eastern Equatorial Pacific Ocean.

You should still have all sixteen Decembers in a stack. If not, create that stack now.

1. Following the instructions in Exercise 1(C), to calibrate the top image in the stack. All the images in the stack will automatically be calibrated and the open diamond will appear to the left of the image name once they are.
2. Choose the freehand selection tool from the tool bar.
3. On the first image in the stack, select the Eastern Equatorial Pacific Ocean, being careful to avoid land and annotations. Your selection should range from about 20S to 20N and from the International Dateline to about -90.
4. Choose Analyze/Reset to clear all measurements.
5. Choose Analyze/Options and select mean and standard deviation.
6. Choose Analyze/Show Results to see the Results window on your screen and position this window so you can see both the images and the results windows.
7. Choose Analyze/Measure.
You will see the mean and standard deviation appear in the Results window, for the region you have selected on the December 1982 image.
8. Use the > key to move to the next window (December 1983) in the stack and notice that your selection automatically appears on this image.
9. Choose Analyze/Measure (or apple1). There are now two measurements in the Results window; one for each month.
10. Use the > key to move through the stack one month at a time, computing the mean and standard deviation for each month by choosing the Analyze/Measure command or apple1.
11. Once you have done this for all twelve months, save the Results window (File/Save As) as Eq_Pac_82_97(measurements).

12. Open the results file in SEE-Image and type in the year in place of the 0.00 in the first column, for each row of measurements.

13. Now, create a plots of these data either by hand or using a plotting package you have access to. For the first one, plot the year on the x-axis and the mean SST on the y-axis. The second plot should also have year plotted on the x-axis. The y-axis of this plot should be the standard deviation for the region.

Write a discussion interpreting the plots, including reasons for the trends and magnitudes of the curves.

C. Using Climatological SST Data to Explore Interannual Variation and El Nino.

You will now work with an interesting data set called a climatology. In meteorological terms, the word climate refers to the average pattern of weather in a region. An example may help. If on a day in July, you are asked, "What's the weather been like in New Orleans?" you might answer, "Today it's clear and cool, but yesterday was hot and muggy." On the other hand, if you are asked, "What's the climate like during the summer in New Orleans?" it would be correct to answer, "In the summer it's hot and muggy." The climate of a region is quantified by computing very long-term averages of the weather of the region.

In the oceans, climatologies are similarly computed. In this exercise, the SST climatology you will be working with was computed as the average of a given month over many years. There are twelve monthly files in this climatology data set of SST. The spatial resolution of this data set is identical to the monthly averaged SST data set you have been working with.

1. Import the twelve climatological SST files, put them into a stack, load the SST color table, and calibrate the top image in the stack. Become familiar with this data set as you have done in other exercises.

The quantitative part of this exercise will involve creating several time-series to observe how the SST in the eastern Equatorial Pacific varies during an El Nino. The class should split into small groups. Each group will gather a time-series of mean SST and standard deviation for a different year (use 1982, 1983, 1996, 1997), including the climatology, for the eastern Equatorial Pacific (do this as in B, above). Then, you will all create one plot of the climatological SST, and all the four individual years, as a function of time. The plot will have 5 curves.

If there is time during lab, try the following:

Do the same time-series exercise as above but with the Western Equatorial Pacific Ocean region and compare your results to the curves for the Eastern Equatorial Pacific Ocean.

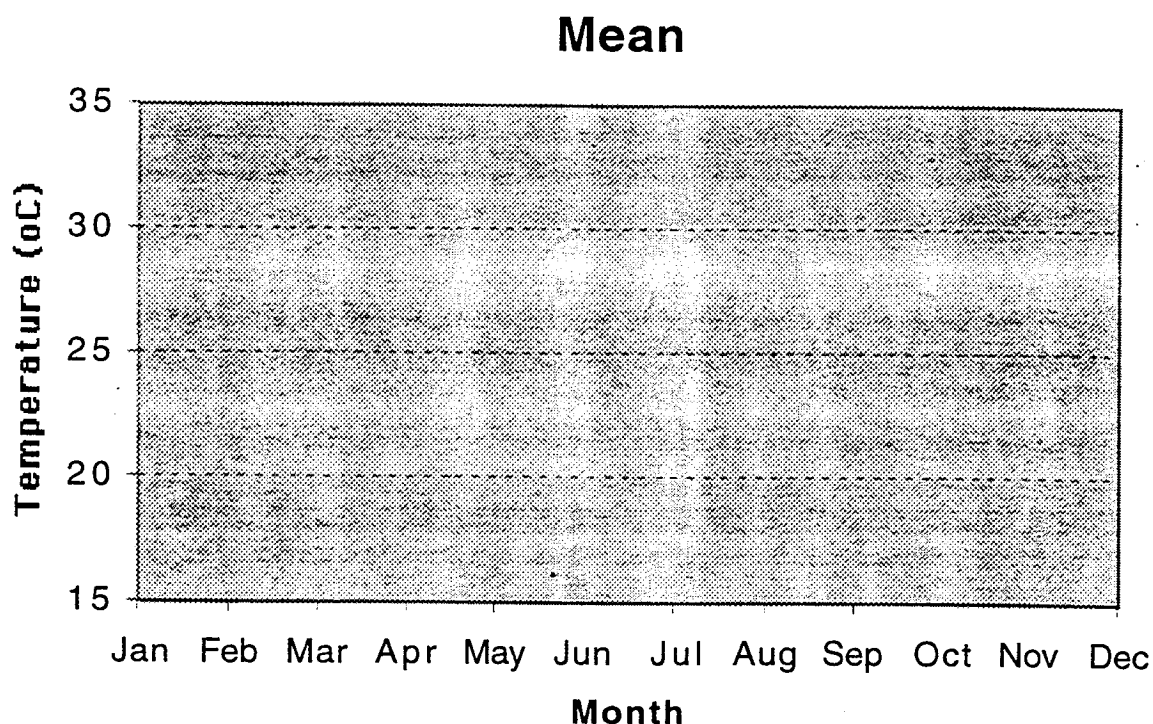
Use 'Image Math' to create **anomaly** fields based on the climatological SST data (as in Exercise 3(F)). For instance, subtract the December climatology from the image for December '82, '83, '96, and '97. Compare these difference (also called anomaly) fields.

G. Creation of a Time-Series of SST to Observe Seasonal Variations

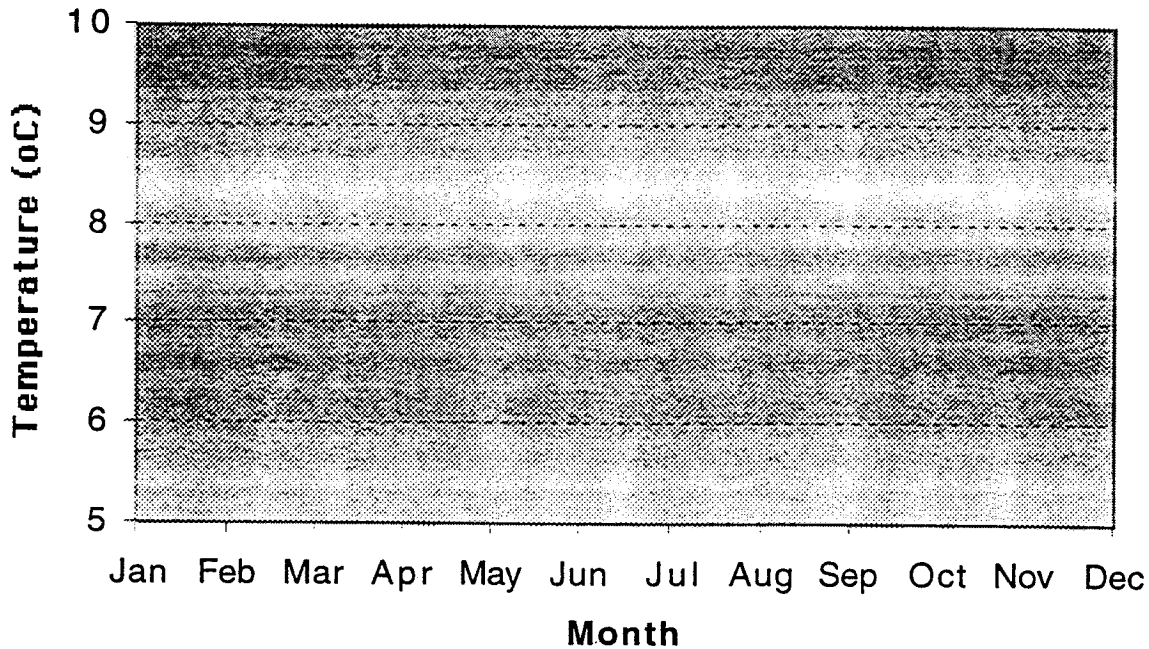
You will now perform some analysis on the monthly SST data which is identical to analyses performed by scientists in their research in order to study the temporal variation of a geophysical parameter. You will use SEE-Image to compute the average SST in a Northern Hemisphere ocean basin for each month, and create a plot of the SST as a function of month. You will do the same thing for a Southern Hemisphere Ocean basin. Comparing the two plots will make clear how the seasons affect SST.

1. As above, open twelve monthly images for 1994.
2. Create a stack of the twelve monthly images and apply the SST color table to it.
3. Calibrate the first image in the stack using the technique described in Exercise 1(C).
4. Draw a solid line across the first image in the stack (which should be January) at the Equator.
5. Choose the freehand selection tool from the tool bar.
6. Select the entire North Pacific Ocean, coming as close the line drawn at the Equator as you can (but DO NOT include that line in your selection).
7. Choose Analyze/Reset to clear all measurements.
8. Choose Analyze/Options and select mean and standard deviation.
9. Choose Analyze/Show Results to see the Results window on your screen and position this window so you can see both the images and the results windows.
10. Choose Analyze/Measure.
You will see the mean and standard deviation appear in the Results window, for the region you have selected on the January image.
11. Use the > key to move to the next window (February) in the stack and notice that your selection automatically appears on this image.
12. Choose Analyze/Measure (or apple1). There are now two measurements in the Results window; one for each month.
13. Use the > key to move through the stack one month at a time, computing the mean and standard deviation for each month by choosing the Analyze/Measure command or apple1.
14. Once you have done this for all twelve months, save the Results window (File/Save As) as North_Pac_97(measurements).
15. Use the < key to position the January image on top once again.
16. Using the free hand selection tool, select a region in the South Pacific Ocean which is similar in size to the region you selected in the North Pacific. DO NOT select the line you have drawn over the equator.

17. Choose Analyze/Reset, and then compute the mean and standard deviation of this region by choosing Analyze/Measure. You should now see one measurement in the Results window.
18. Using the > key to advance one image at a time through the stack, and the Analyze/Measure command to compute the statistics, do this for all twelve months.
19. Save these results as South_Pac_97(measurements).
20. Open the two results files and type in the name of the month in place of the 0.00 in the first column, for each row of measurements.
21. Now, create two plots of these data either by hand (use the figures below to guide you) or using a plotting package you have access to. For the first one, plot month on the x-axis and the mean SST on the y-axis for both the North Pacific and South Pacific (one set of axes, with two plots of mean SST). The second plot should also have month plotted on the x-axis. The y-axis of this plot should be the standard deviation for the North Pacific and the South Pacific.



Standard Deviation



Write a discussion interpreting the plots, including reasons for the trends and magnitudes of the curves.

Here's an idea for additional exploration of the seasonal variability in SST:

Select other regions of the world's oceans, create time-series as described above, and then discuss the reasons for the variation in the seasonal cycle among regions.

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EXERCISE 4 Observation of the year-to-year, or interannual, variation of SST

A. Qualitative Observations of Long-term Interannual Variability

1. Locate the folder labeled "Decembers" on your hard disk.
2. Choose File/Import and check 'open all' in the dialog box to open all the December images for all sixteen years from 1982-1997.
3. Choose Options/Color Table/SST to apply a color palette to the top image .
4. Choose Options/Propagate/Look-Up Table to apply this color table to all opened images.

Steps 5 and 6 will create a stack containing all of the December images, with the filenames displayed on each image in the stack:

5. Choose Options/Preferences and click on 'Display slice titles only'
6. Choose Stacks/Windows to Stack to create a stack with the filenames displayed.

Using the tools in SEE-Image which you are familiar with from the first three exercises, explore the long-term variation of the global SST and record your observations. Here are some suggestions for your exploration:

Start by simply moving through the stack one image at a time using the < and > keys (these are also the comma and period keys, respectively) until you are familiar with the data and can record some general comments about the SST throughout the sixteen year period.

Use the density slice tool (Exercise 2(B)) to highlight the warmest (coolest) SSTs and observe how they vary throughout the years. Are there any years which appear warmer (cooler) than others, on average?

Create a montage from the images in the stack and use the selection and drawing tools to isolate regions (the Equatorial Pacific is a good region to look at) in order to make it easier to compare them visually (see Exercise 3(D)). Remember, a selection made on the top image in the stack automatically appears on every image in the stack when it is displayed.

7. Choose/Stacks/Make Montage... and enter the following information in the dialog box:
Columns: 4
Rows: 4 (2, if you want to look at the first 8 years initially)
Scale Factor: 0
First Slice: 1
Last Slice: 16 (8, if you want to look at the first 8 years initially)
Increment: 1
Check "Borders".
Do not check "Number Slices".
Click "OK".

It might be easier to look at just 8 years at a time in the montage (modify the Rows and Last Slice information in the Montage dialog box as shown above). Record your observations.

If you drew lines on the images in the Montage, or altered them by cutting out sections, now is the time to close this montage and work again with the original stack of 16 December images.

Finally, create a movie of the 16 years and record anything new you observe.

8. Choose Stacks/Animate.

Which years look anomalous? Why? Which SEE-Image tool(s) make it easier for you to observe the anomalous data? Can you make some general comments about long-term oceanographic variability of SST?

B. Quantitative Observations of Long-term Interannual Variability in the Eastern Equatorial Pacific Ocean

As you probably figured out, even though the eye is a very sensitive instrument, it is hard to observe very subtle changes in SST from year-to-year. That is why scientists also use quantitative techniques involving statistics and the creation of time-series to discern such changes. You will now create some time-series of mean SST and standard deviation, for a very interesting region of the earth's oceans, the Eastern Equatorial Pacific Ocean.

You should still have all sixteen Decembers in a stack. If not, create that stack now.

1. Following the instructions in Exercise 1(C), to calibrate the top image in the stack. All the images in the stack will automatically be calibrated and the open diamond will appear to the left of the image name once they are.
2. Choose the freehand selection tool from the tool bar.
3. On the first image in the stack, select the Eastern Equatorial Pacific Ocean, being careful to avoid land and annotations. Your selection should range from about 20S to 20N and from the International Dateline to about -90.
4. Choose Analyze/Reset to clear all measurements.
5. Choose Analyze/Options and select mean and standard deviation.
6. Choose Analyze/Show Results to see the Results window on your screen and position this window so you can see both the images and the results windows.
7. Choose Analyze/Measure.
You will see the mean and standard deviation appear in the Results window, for the region you have selected on the December 1982 image.
8. Use the > key to move to the next window (December 1983) in the stack and notice that your selection automatically appears on this image.
9. Choose Analyze/Measure (or apple1). There are now two measurements in the Results window; one for each month.
10. Use the > key to move through the stack one month at a time, computing the mean and standard deviation for each month by choosing the Analyze/Measure command or apple1.
11. Once you have done this for all twelve months, save the Results window (File/Save As) as Eq_Pac_82_97(measurements).

12. Open the results file in SEE-Image and type in the year in place of the 0.00 in the first column, for each row of measurements.

13. Now, create a plots of these data either by hand or using a plotting package you have access to. For the first one, plot the year on the x-axis and the mean SST on the y-axis. The second plot should also have year plotted on the x-axis. The y-axis of this plot should be the standard deviation for the region.

Write a discussion interpreting the plots, including reasons for the trends and magnitudes of the curves.

C. Using Climatological SST Data to Explore Interannual Variation and El Nino.

You will now work with an interesting data set called a climatology. In meteorological terms, the word climate refers to the average pattern of weather in a region. An example may help. If on a day in July, you are asked, "What's the weather been like in New Orleans?" you might answer, "Today it's clear and cool, but yesterday was hot and muggy." On the other hand, if you are asked, "What's the climate like during the summer in New Orleans?" it would be correct to answer, "In the summer it's hot and muggy." The climate of a region is quantified by computing very long-term averages of the weather of the region.

In the oceans, climatologies are similarly computed. In this exercise, the SST climatology you will be working with was computed as the average of a given month over many years. There are twelve monthly files in this climatology data set of SST. The spatial resolution of this data set is identical to the monthly averaged SST data set you have been working with.

1. Import the twelve climatological SST files, put them into a stack, load the SST color table, and calibrate the top image in the stack. Become familiar with this data set as you have done in other exercises.

The quantitative part of this exercise will involve creating several time-series to observe how the SST in the eastern Equatorial Pacific varies during an El Nino. The class should split into small groups. Each group will gather a time-series of mean SST and standard deviation for a different year (use 1982, 1983, 1996, 1997), including the climatology, for the eastern Equatorial Pacific (do this as in B, above). Then, you will all create one plot of the climatological SST, and all the four individual years, as a function of time. The plot will have 5 curves.

If there is time during lab, try the following:

Do the same time-series exercise as above but with the Western Equatorial Pacific Ocean region and compare your results to the curves for the Eastern Equatorial Pacific Ocean.

Use 'Image Math' to create **anomaly** fields based on the climatological SST data (as in Exercise 3(F)). For instance, subtract the December climatology from the image for December '82, '83, '96, and '97. Compare these difference (also called anomaly) fields.

Polar Sea Ice Observations - Exercises

A. Northern Hemisphere Distribution and Seasonal Variability

Load 12 Northern Hemisphere Monthly Mean Images. Place them into a Stack. Use Animate and/or Make Montage to visually inspect the general Northern Hemisphere sea ice distribution, and answer the following questions:

1. What month is the sea ice areal extent a maximum? A minimum?
2. In general terms, describe how the sea ice extent grows from September to March (i.e., Is it a steady growth rate, or does it start growing quickly then more slowly later? Where does it start growing? Where are the largest initial changes?).
3. Describe the sea ice distribution in the Barents and Norwegian Seas, in late winter (February-March) and use your knowledge of physical oceanography (i.e., the circulation) to explain it.
4. Compare the sea ice distribution along the east and west coast of Greenland in late winter (north/south as well as onshore/offshore extent), and use your knowledge of physical oceanography (i.e., the circulation) to explain it.
5. In general terms, describe how the sea ice extent melts/recedes from March to September (i.e., Is it a steady melt rate, or does it start melting quickly then more slowly later? Where does it start melting? Where are the largest initial changes? Hint - Look at locations of polynyas.).
6. Looking at the total annual cycle, where does the ice edge change the most from the summer minimum sea ice extent to the late winter maximum sea ice extent? Where does it change the least? What is your best explanation for this?
7. Describe the marginal ice zone (MIZ) during freeze-up (winter). Is it wide? Is it narrow? Does the ice concentration vary rapidly or slowly across the MIZ?

Close the Stack. The following two exercises look at the seasonal changes in the Northern Hemisphere sea ice cover in a more quantitative fashion.

-Open the maximum ice concentration image (15 March 1991).

-Use the SET SCALE command under the ANALYZE menu bar to calibrate 1 pixel = 25 kilometers.

Select km for units.

Measured distance = 1.

Known distance = 25.


-Import the minimum ice concentration image (01 September 1990).

-Use the SET SCALE command to calibrate 1 pixel = 25 kilometers.

8. Using the Density Slice Tool on the Maximum and Minimum images, find the total areal extent, and calculate the % difference.

-Select FIND EDGES from the PROCESS menu bar to trace the edge of the minimum ice concentration.

-Overlay the minimum ice concentration edge ON TO the maximum ice concentration image.

-Use the straight line selection tool () to measure the distance from minimum ice edge in the Arctic Ocean to maximum ice edge in the Bering AND the Barents/Norwegian Sea (i.e. two separate measurements). Put the cursor on the point you want to begin the measurement from, click the mouse button, hold it down, and drag the cursor to the end point of your measurement.

-Select MEASURE from the ANALYZE menu bar.

-The measurement information appears in the RESULTS WINDOW.

9. Distance from sea ice edge in September (minimum) to March (maximum) sea ice extent in Bering Sea =

Growth rate (km/day) =

Distance from sea ice edge in September (minimum) to March (maximum) sea ice extent in Barents Sea =

Growth rate (km/day) =

B. Southern Hemisphere Seasonal Variability

Load 12 Southern Hemisphere Monthly Mean Images. Place them into a Stack. Use Animate and/or Make Montage to visually inspect the general Southern Hemisphere sea ice distribution, and answer the following questions:

1. What month is the sea ice areal extent a maximum? A minimum?

2. In general terms, describe how the sea ice extent grows from February to September (i.e., Is it a steady growth rate, or does it start growing quickly then more slowly later? Where does it start growing? Where are the largest initial changes?).
3. In general terms, describe how the sea ice extent melts from September to March (i.e., Is it a steady melt rate, or does it start melting quickly then more slowly later? Where does it start melting? Where are the largest initial changes?).
4. Describe the marginal ice zone (MIZ) during freeze-up (winter). Is it wide? Is it narrow? Does the ice concentration vary rapidly or slowly across the MIZ? Compare the MIZ for the Antarctic to the MIZ for the Arctic.

Close the Stack. The following two exercises look at the seasonal changes in the Southern Hemisphere sea ice cover in a more quantitative fashion.

- Open the maximum ice concentration image.
 - Use the SET SCALE command under the ANALYZE menu bar to calibrate 1 pixel = 25 kilometers.
Select km for units.
Measured distance = 1.
Known distance = 25.
 - Import the minimum ice concentration image.
 - Use the SET SCALE command to calibrate 1 pixel = 25 kilometers.
5. Using the Density Slice Tool on the Maximum and Minimum images, find the total areal extent, and calculate the % difference. Compare to the Northern Hemisphere
- Select FIND EDGES from the PROCESS menu bar to trace the edge of the minimum ice concentration.
 - Overlay the minimum ice concentration edge ON TO the maximum ice concentration image.
6. Measure the distance from minimum ice edge in the Antarctic Ocean to maximum ice edge in the Weddell Sea Sector, Indian Ocean Sector, Western Pacific Sector, and Ross Sea Sector (Figure 5.) (i.e. four separate measurements).

Distance from sea ice edge in March (minimum) to October (maximum) sea ice extent in Weddell Sea Sector =

Growth rate (km/day) =

Distance from sea ice edge in March (minimum) to October (maximum) sea ice extent in Indian Ocean Sector =

Growth rate (km/day) =

Distance from sea ice edge in March (minimum) to October (maximum) sea ice extent in Western Pacific Ocean Sector =

Growth rate (km/day) =

Distance from sea ice edge in March (minimum) to October (maximum) sea ice extent in Ross Sea Sector =

Growth rate (km/day) =

Compare growth rates to those found in the Northern Hemisphere.

C. Northern Hemisphere Interannual Variability

Load Months with Maximum Sea Ice Extent for the Years ____ to _____. Place them into a Stack. Use Animate and/or Make Montage to visually inspect the general interannual variability in the Northern Hemisphere sea ice distribution, and answer the following questions:

1. Which years had the largest ice extent in the Barents Sea? In the Bering Sea? In the Sea of Okhotsk?
2. Which years had the smallest ice extent in the Barents Sea? In the Bering Sea? In the Sea of Okhotsk?

Using the Density Slice Tool, measure the sea ice areal extent in different years.

3. Compare your results with published data (Figure 4).
4. Which year had the largest sea ice extent? The least? What is the percent difference between the two years?

Compare the maximum sea ice areal extent in different years to a climatological maximum sea ice extent using Image Math (Subtract annual images from climatology).

D. Southern Hemisphere Interannual Variability

Load Months with Maximum Sea Ice Extent for the Years ____ to _____. Place them into a Stack. Using the Density Slice Tool, measure the sea ice areal extent in different years.

1. Compare your results with published data (Figure 4).
2. Which year had the largest sea ice extent? The least? What is the percent difference between the two years?

Compare the maximum sea ice areal extent in different years to a climatological maximum sea ice extent using Image Math (Subtract annual images from climatology).

E. Polynyas

Load 12 Northern Hemisphere Monthly Mean Images. Place them into a Stack. Use Animate and/or Make Montage to answer the following question:

1. Identify the locations and periods of polynyas.
2. Select an area in and outside of a polynya. Generate a ice concentration time series for each area. Look at percent change in ice concentration/variability for each area.